DESIGN OF SEGMENTED OUTER ROTOR PERMANENT MAGNET FLUX SWITCHING MOTOR IN TRANSVERSE SHAPE FOR HIGH TORQUE APPLICATIONS

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A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy in Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

MARCH 2020

This thesis is dedicated to my family for her patience and prayers

ACKNOWLEDGEMENT

My Ph.D research work started as something that would not come to an end one day. I am thankful to my Institution for approving my application and provision of fund for the programme. In this research, I must admit that the experience of travelling to an unknown faraway place, for the first time in life, is not easy. One may likely miss the right road many times, forcing him to wander around and about many times in order to find the right way. It happened in my journey.

In everything I experienced, I am very grateful to my supervisor, Associate Prof. Dr. Erwan Sulaiman for accepting me to be one of his students. He was always willing to tell me to be courageous and do it this way and that way. In all the ways, they led to success. His guidance and support during the entire study made it possible for me to write this thesis. I am continually amazed by his wealth of knowledge, his discipline, research and technical skills.

At the Research Centre for Applied Electromagnetics, I wish to express my sincere thanks to the following colleagues: Faisal Khan who never turned me down whenever I went to him with questions and Md Zarafi Ahmad for every advice he offered in the difficult research process. Every member at the research centre has been greatly acknowledged. They include, Siti, Laili, Naufaul, Hassan, Irfan, Firdaus, Fairos and Abdul Rashid Omar Mumin. There are other friends whose names I would not mention due to lack of space. They provided useful information during my research time period.

In a very special way, I express my sincere gratitude to my wonderful family for being patient during my absence. Lastly, I did not forget everyone I did not know, for sure, whatever they did was helpful to raise up hope.

ABSTRACT

The use of an outer rotor electric motor for electric vehicle applications has gained a lot of attention since the motor has high torque density and power. Outer rotor motors have performance indices that should be taken into consideration because not every machine is effective. Recently, outer rotor hybrid excitation flux switching motor (OR-HEFSM) in salient rotor has become attractive for providing high torque and high power. It uses two flux sources and single tooth winding. Regrettably, salient rotor and complex stator of HEFSM with single tooth winding have inherited high iron loss and high winding loss. Furthermore, HEFSM uses a high volume of permanent magnet (PM), suffers demagnetisation and low permeability resulting in poor performance. In another development, outer rotor field excitation FSM (OR-FEFSM), using dovetail segmented rotor in concentrated winding, has been presented for low-cost and high power-density. The OR-FEFSM using concentrated winding is capable of providing high power-density and sinusoidal back-emf, reasonable torque ripple and high net peak-torque. However, the problem of ORFEFSM is the utilisation of high number of stator teeth, high number of rotor segments and high number of copper conductor. These high materials usage lead to high iron and copper losses that affect performance of motor. This thesis deals with a newly designed structure of the segmented outer rotor permanent magnet flux switching motor in transverse shape (SegOR-PMFSM) with minimal iron and copper losses, high permeability, high torque and power output. The JMAG-Designer version 14 is utilised as the 2D finite element analysis (2D-FEA). For the three-phase operation, a 24 stator-teeth with feasible poles like 8, 10, 14, 16, 22 and 26 was designed, analysed and the results were compared based on torque and power performances. The 24S/14P motor is selected for securing the initial highest torque of 240.5 Nm and achieved the target average torque/power of 470 Nm/45 kW after using parameter optimisation method (POM). This result was compared with OR-HEFSM having torque/power of 335 Nm/123 kW and OR-FEFSM having torque/power of 380 Nm/29 kW. Meanwhile, the torque achieved with SegOR-

PMFSM is 28.72 % and 19.14 % higher than OR-HEFSM and OR-FEFSM. Motor's torque density and power density, at maximum armature current density are calculated to be 76.66 kNm/m^3 and 7339.5 kW/m^3 respectively. Therefore, the torque of 24S/14P topology in a segmented transverse shape has produced higher average torque than using salient rotor pole and dovetail segmented rotor in the machine design. The results obtained affirm good agreement with high torque for light-weight electric vehicle applications. The favourable high torque and power output of the proposed SegOR-PMFSM present it as a viable core component for electric vehicle application. However, this research is limited to 2D simulation analysis without experimental evaluations due to none availability of the testing equipment and the motor's weakness is potential high induced emf.

ABSTRAK

Penggunaan motor elektrik pemutar luar bagi aplikasi kenderaan elektrik telah mendapat banyak perhatian kerana motor seperti ini mempunyai kuasa dan ketumpatan tork yang tinggi. Motor pemutar luar mempunyai indeks prestasi yang perlu dipertimbangkan kerana tidak setiap mesin berkesan. Baru-baru ini, pengayun fluks pengujaan pemutar luar (OR-HEFSM) di pemutar utama menjadi tarikan dalam penghasilan tork dan kuasa yang tinggi. Ia menggunakan dua sumber fluks dan penggulungan gigi tunggal. Malangnya, pemutar utama dan pemegun kompleks HEFSM dengan penggulungan gigi tunggal telah memiliki kehilangan besi dan penggulungan yang tinggi. Tambahan pula, HEFSM menggunakan jumlah magnet kekal (PM) yang tinggi, mengalami demagnetisasi dan kebolehtelapan yang rendah menyebabkan prestasi menjadi lemah. Dalam perkembangan lain, medan pengujaan pemutar luar FSM (OR-FEFSM), degan menggunakan pemutar teruas ekor merpati dalam penggulungan terpumpum, telah dibentangkan untuk kos yang rendah dan ketumpatan kuasa yang tinggi. OR-FEFSM menggunakan penggulungan terpumpum mampu menyediakan ketumpatan kuasa tinggi dan back-emf berbentuk sinus, riak tork yang munasabah dan tork puncak tinggi yang tinggi. Walau bagaimanapun, masalah OR-FEFSM adalah penggunaan jumlah gigi pemegun yang tinggi, semen pemutar yang tinggi dan bilangan konduktor tembaga yang tinggi. Penggunaan bahan yang tinggi ini membawa kepada kehilangan besi dan tembaga yang banyak yang mempengaruhi prestasi motor. Tesis ini berkaitan dengan struktur reka betuk yang baru bagi motor penukaran fluks magnet pemutar kekal dalam bentuk melintang (SegOR-PMFSM) dengan kehilangan besi dan tembaga yang minimum, kebolehtelapan yang tinggi, tork dan keluaran kuasa yang tinggi. JMAG –Designer versi 14 digunakan sebagai analisis unsur terhingga 2D (2D-FEA). Bagi operasi tiga fasa, 24 gigi stator dengan kutub yang layak seperti 8, 10, 14, 16, 22 dan 26 direka bentuk, dianalisis dan keputusannya dibandingkan dengan tork dan prestasi kuasa. Motor 24S/14P dipilih untuk menguasai tork tertinggi yang awal iaitu 240.5 Nm dan

mencapai sasaran purata tork/kuasa 470 Nm/45 kW selepas mennunakan kaedah pengotimuman parameter (POM). Hasil ini dibandingkan dengan OR-HEFSM yang mempunyai tork/kuasa 335 Nm/123 kW dan OR-FEFSM mempunyai tork/kuasa 380 Nm/29 kW. Sementara itu, tork yang dicapai dengan SegOR-PMFSM adalah 28.72 % dan 19.14 % lebih tinggi daripada OR-HEFSM dan OR-FEFSM. Ketumpatan tork dan kuasa motor, pada kepadatan arus maksimum yang dikira masing-masing adalah 76.66 kNm/m^3 dan 7339.5 kW/m^3. Oleh itu, tork bagi topologi 24S/14P dalam bentuk melintang telah menghasilkan tork purata yang lebih tinggi daripada menggunakan kutub rotor pemutar dan pemutar teruas ekor merpati dalam reka bentuk mesin. Hasil yang diperolehi mengesahkan perjanjian yang baik dengan tork yang tinggi untuk aplikasi kenderraan elektrik ringan. Tork dan keluaran kuasa yang tinggi bagi SegOR-PMFSM yang dicadangkan itu sebagai komponen teras yang berdaya maju untuk aplikasi kenderaan elektrik. Walau bagaimanapun, kajian ini adalah terhad kepada analisis simulasi 2D tanpa penilaian eksperimen kerana tiada peralatan ujian dan kelemahan motor yang memiliki poteni emf yang tinggi.

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LIST OF SYMBOLS AND ABBREVIATIONS

ψ_d	-	d-axis flux linkage
ψ_q	-	q-axis flux linkage
ψ_m	-	Magnitude of fundamental component
α	-	Filling factor of armature coil
ϕ_a	-	Aligned flux
θ_a	-	Rotor position between U1 and d-axis
Φ_P	-	Flux per pole
θ_r	-	Electrical angular position of rotor
θ_s	-	Segment angle span
ω_r	-	Rotor rotational speed
η	-	Efficiency
η_a	-	Hysteresis coefficient
ρ	-	Copper resistivity
a.c	-	Armature conductor
A1	-	Armature slot width
A2	-	Armature slot length
B_{ave}	-	Specific magnetic loading
B_{max}	-	Maximum flux density
C_o	-	Output coefficient
D_{or}	-	Outer rotor diameter
E_{ph}	-	Voltage output per phase
f_e	-	Electrical frequency

f_m	-	Mechanical rotational frequency
I_a	-	Armature current
I_d	-	d-axis current
I_{ph}	-	Current per phase
I_q	-	q-axis current
I_1	-	Current carrying conductor
I	-	Peak phase current
J_a	-	Armature current density
k_e	-	Eddy current constant
kW	-	Kilowatt
L_a	-	Stack-length
L_o	-	Magnitude component of self-inductance
L_{-end}	-	Estimate air-gap length
N_a	-	Number of turns
N_{a-slot}	-	Number of armature slot
P_c	-	Copper loss
P_d	-	Power developed
P_e	-	Eddy current loss
P_h	-	Hysteresis loss
P_i	-	Iron loss
P_{in}	-	Electrical power
P_o	-	Power output
P_{out}	-	Electrical power developed
P_{loss}	-	Machine power loss
R_c	-	Resistance of winding coil
P_r	-	Rotor pole number
$M1$	-	Length of permanent magnet
$M2$	-	Width of permanent magnet
rms	-	Root mean square
rps	-	Revolution per second
mmf	-	Magnetomotive force

S_a	-	Armature slot area
t	-	Time
t_a	-	Thickness of material
T_{em}	-	Electromagnetic torque
T_d	-	Torque developed
V_1	-	Volume of coil slot
V_2	-	Volume of coil end
W_a	-	Armature coil copper
SegOR	-	Segmented outer rotor
SegStator	-	Segmented stator
D	-	Distance of inner rotor radius
D1	-	Length of rotor segment
DFT	-	Discrete fourier transform
POM	-	Parameter optimisation method
DC	-	Direct current
EM	-	Electric motor
EV	-	Electric vehicle
FEV	-	Full electric vehicle
FEA	-	Finite element analysis
FEFSM	-	Field excitation flux switching motor
FSM	-	Flux switching motor
HEFSM	-	Hybrid excitation flux switching motor
ICE	-	Internal combustion engine
IPMSM	-	Interior permanent magnet synchronous motor
IM	-	Induction motor
PM	-	Permanent magnet
PMFSM	-	Permanent magnet flux switching motor
Q	-	Output equation
SegOR-PMFSM	-	Segmented outer rotor permanent magnet flux switching motor
SRM	-	Switched reluctance motor
W	-	Width of rotor segment
V	-	Total volume of coil
Z	-	Number of conductors per phase

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CHAPTER 1

INTRODUCTION

1.1 Research background

It is obvious that the use of electric motor (EM) is so much important in our world, economically and environmentally for innovative development. As a result, great advances have been made in improving the performance of electric motors in order to be suitable for applications such as automotive and aerospace. These improvements are in the aspect of torque, power, efficiency, speed range, reliability and controllability [1-3]. For automotive applications without gearing, the requirements include high torque, high efficiency, high precision, less heat loss, less weight, little use of start-up energy and less vibration. Therefore, high torque electric motors are used for automotive application such as light weight fully electric vehicle (FEV) [4-7]. Outer rotor motor application is one of the solutions for saving energy and sustaining greenhouse vehicles [8]. EM provides torque and speed for applications and has proven to be a core component in this development and transformation process [9-11]. Torque of EM determines its performance and category of applications therefore, research for high torque motors is crucially significant for sustainable applications. The latest research and development have made possible many in-wheel automotive applications to be equipped with high torque electric motors [12,13].

Permanent magnet synchronous motor (PMSM) is used for automotive applications due to its superior magnetic properties such as high torque density, high torque, high efficiency, wide speed range and maintenance free operation but it locates active materials on the rotor [14-17]. The drawbacks of PMSM include increased high PM volume, limited field weakening capability, reduced slot surface area and high heat loss [18-20]. Meanwhile, segmented stator outer rotor permanent magnet

synchronous motor (SegStator-ORPMSM) has been proposed for light weight in-wheel application [21]. SegStator-ORPMSM consists of a four-cell segmented stator core. It uses all-stator teeth armature winding with permanent magnet (PM) mounted on the rotor. SegStator-ORPMSM is capable of high flux density, high torque and efficiency, but it has high material usage with PMs mounted on the rotating rotor which obviously affect the performance at speedy operation. Obviously, many electric motors have been developed but performance indices have to be taken into consideration because not every motor design is effective [22-24].

In another development, flux switching motor (FSM) is an advanced form of synchronous motor (SM) built by combining the structures of switched reluctance machine and inductor alternator with no active material located on the rotor [25-27]. FSM has internal three types which are (1) Permanent Magnet FSM (PMFSM) using PM flux source, (2) Field Excitation FSM (FEFSM) using field coil source and (3) Hybrid Excitation FSM (HEFSM) using both PM and field coil excitation sources. [28-31]. Due to its construction and characteristics, FSM has the advantages of less material usage, light weight and speed operation. Characteristically, FSM operates with a double electrical frequency and has attracted researchers' interest around the world [32-34].

Over the years, PMFSM has attracted attention due to its advantage of free-loss excitation. PMFSM has been designed in both inner and outer rotor configurations for various application. For automotive application, Fei *et al.* in [35] proposed three-phase Outer Rotor PMFSM (OR-PMFSM) for high torque density. It consists of C-stator core in which PMs in circumferential pattern are sandwiched between segment stator teeth. OR-PMFSM has benefit of high density but performance is affected by the use of C-core which reduces armature slot area [36]. In the same vein, the Outer Rotor HEFSM (OR-HEFSM) [37] in salient rotor has been proposed for high torque and power densities. It utilises two flux sources and requires external circuitry connection for excitation [37]. Consequently, OR-HEFSM has drawbacks of high iron loss and high winding loss, high flux leakage, poor temperature management and low armature reaction [38-39]. Furthermore, Outer Rotor FEFSM (OR-FEFSM) using segmented rotor in dovetail shape [40] has been proposed for high power density applications. OR-FEFSM replaced the PM in OR-PMFSM with field coil control capabilities. The use of rotor segment is to overcome high iron loss and weight associated with salient rotor regime [41]. OR-FEFSM has the advantage of low-cost

but requires an external DC source for excitation. It is obvious that both OR-HEFSM and OR-FEFSM require external DC source which increases winding loss and motor weight. Therefore, utilising the benefit of loss free excitation and reducing PM volume by 20 %, PMFSM would be discussed in this thesis. It is desirable to reduce iron loss in the salient rotor by replacing with segmented rotor in transverse shape and alternate tooth armature winding for high torque performance.

1.2 Problem statements

Outer rotor motors are becoming popular because they rotate slowly to overcome inertia and generate high torque for sustainable automotive applications [42]. Figure 1.1 depicts structures of outer rotor motors in segmented, salient and round rotors.

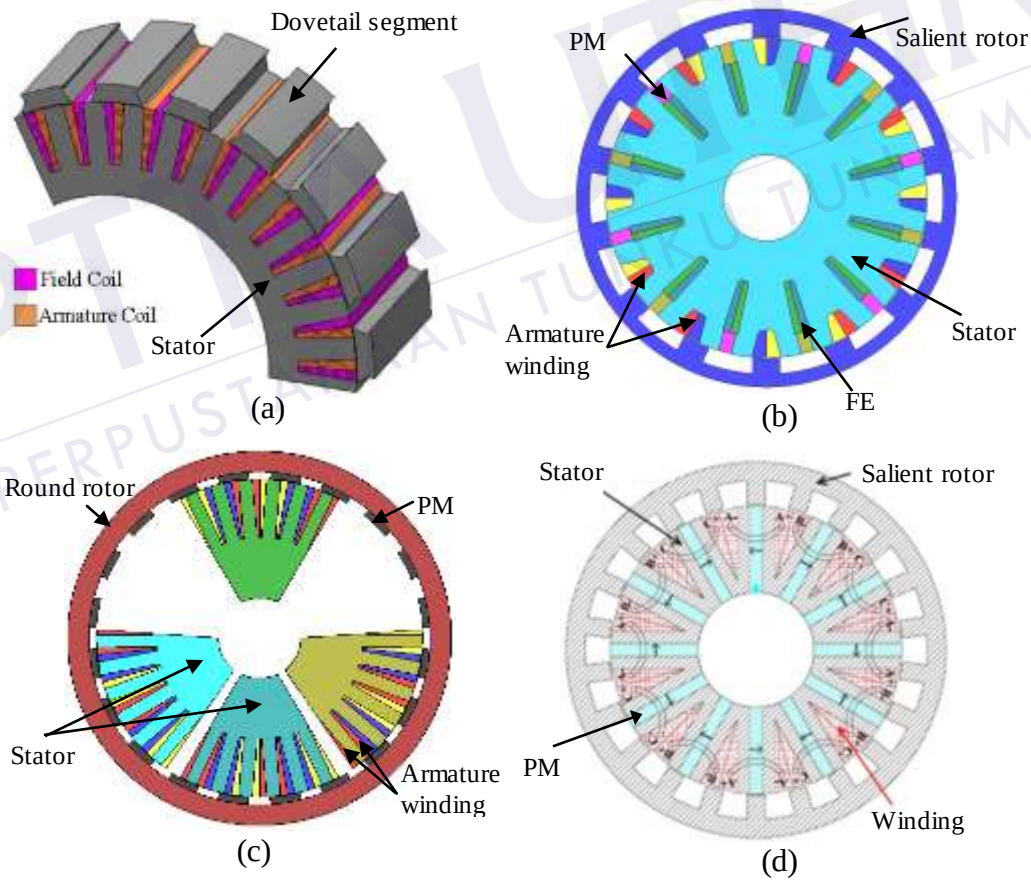

Figure 1.1: Cross-sections of three-phase outer rotor motors (a) OR-FEFSM (segmented rotor) [40] (b) OR-HEFSM (salient rotor) [37] (c) (d) SegStator-ORPMSM (round rotor) [21] OR-PMFSM (salient rotor) [35]

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APPENDIX A

LIST OF PUBLICATIONS AND AWARDS

Following is the list of publications in the result of research presented in this thesis.

Journals

[1] Enwelum I Mbadiwe; Erwan Sulaiman "Flux Switching Permanent Magnet Motor using Segmented Outer Rotor Structure for Electric Scooter" Indonesian Journal of Electrical Engineering and Computer Science, Vol. 6, No. 2, May 2017, pp. 379 ~ 386 DOI: 10.11591/ijeecs.v6.i2. pp379-386. (Scopus indexed)

[2] Enwelum I Mbadiwe; Erwan Sulaiman; Ahmad Md Zarafi; Siti Khalidah Rahimi, "High Torque Flux Switching Permanent Magnet Machine in Segmented Outer Rotor using Appropriate Split Ratio for Electric Scooter Propulsion" International Journal on Power Electronics and Drives Systems (IJEPDS) Vol 8, No 4: December 2017. (Scopus indexed)

[3] Enwelum I. Mbadiwe and Erwan Sulaiman, "Evaluation of Performance of Flux Switching Motor in Segmented Rotor Using Permanent Magnet for Direct Drive," International Journal of Engineering and Technology, www.sciencepubco.com/index.php/ijet/article/view/22328. (Scopus indexed)

[4] Enwelum I. Mbadiwe, Erwan B. Sulaiman, Ahmad Md. Zarafi, "Torque Performance Analysis of Three-Phase Permanent Magnet Flux Switching Motor in Out-runner Segmented Rotor for In-Wheel High Torque Vehicles," International Journal of Electrical and Electronic Engineering & Telecommunications, Vol. 8, No. 1, pp. 14-18, January 2019. Doi: 10.18178/ijeetc.8.1.14-18. (Scopus indexed)

[5] Enwelum I. Mbadiwe and Erwan Sulaiman, "Permanent Magnet Switched Flux Motor Torque Capability: A Reliable Solution to Fueless Vehicle Application", International Journal of Renewable Energy Resources, 7(1), 8-14, 2018. (Scopus indexed)

[6] Enwelum I. Mbadiwe, Erwan B. Sulaiman, Liew Chung Peng. "Sustainable High Torque for Electric Scooter Propulsion Using Permanent Magnet Flux Switching Machine Technology," Journal of Engineering Science and

Technology Special Issue on SU18, February (2019) 286 – 299. (Scopus indexed)

Proceeding

[7] Enwelum I Mbadiwe; Erwan Sulaiman; Ahmad Md Zarafi, "A High Torque Segmented Outer Rotor Permanent Magnet Flux Switching Motor for Motorcycle Propulsion" Malaysian Technical Universities Conference on Engineering and Technology, December 2017, in MATEC Web of Conferences.

[8] Enwelum I. Mbadiwe and Erwan Sulaiman "Improved Design of Outer Rotor Machine in PM Technology for Motor-Bike Drive Application"2018 IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE) IEEE Xplore: 09 July 2018. (Scopus indexed)

[9] EI Mbadiwe, E Sulaiman, F Khan "Consideration of permanent magnet flux switching motor in segmented rotor for in-wheel vehicle propulsion, International Conference on Computing, Mathematics and Engineering Technologies, 2018 - ieeexplore.ieee.org. (Scopus indexed).

[10] Enwelum I. Mbadiwe and Erwan Sulaiman. "Sustainable Electric Machine Torque Performance using Segmented Rotor and PM Technology for Direct Drive Vehicle Application," 2019 IEEE International Conference on Automatic Control and Intelligent Systems (I^2CACIS), Selangor, Malaysia, 2019, pp. 118-122. (Scopus indexed).

[11] Enwelum I. Mbadiwe, L. Iwani Jusoh, S. M. Naufal and E. Sulaiman, "High Performance Flux Switching Machine using Segmented Rotor and PM Technology for In-Wheel Motorcycle and Scooter Applications," 2019 IEEE 15th International Colloquium on Signal Processing & Its Applications (CSPA), Penang, Malaysia, 2019, pp. 168-173. (Scopus indexed).

[12] Enwelum I. Mbadiwe, Syed Muhammad Naufal bin Syed Othman, Erwan bin Sulaiman. Comparative Study of PM Flux Switching and Surface Mounted PM Synchronous Machines for Direct-drive Vehicle Applications. 2019 IEEE 10th Control and System Graduate Research Colloquium (ICSGRC), Shah Alam, Malaysia, 2019, pp. 41-45. doi: 10.1109/ICSGRC.2019.8837057.

[13] Enwelum I. Mbadiwe and Erwan Sulaiman, A review of various structures and performances of flux switching machine in salient and segmented rotors using PM for EV applications, IEEE Access. ISI Technical Paper, *Under review*

[14] Erwan Sulaiman and Enwelum I. Mbadiwe, Design and Optimization of Outer-Rotor Permanent Magnet Flux Switching Motor using Transverse Segmental Rotor for Automotive Applications, IETPA Electric Power Applications. Research paper *Under Review*. (ISI)

Awards

Silver Medal ITEX KLCC May 2016.

Exhibition & Seminars Product Showcase, Exhibition, Innovation, Invention, UTHM RISE 2018, Nov 13-14/2018 "BRONZE MEDAL"

Best Paper Presenter in 2019 CSPA at Penang, Malaysia on March 8/2019.

RISE 2019, September GOLD MEDAL and PRIZE.